INVESTIGATION OF STRUCTURAL WOOD IGNITION BY FIREBRAND ACCUMULATION

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ABSTRACT

This study aims to understand the process of ignition of wooden structures by ember accumulation during wildfires. The work analyses two different sets of experiments. A high intensity large scale prescribed fire was conducted in a pine stand where ember collection plots were used to collect embers falling on the ground to measure and weigh them. Most of the particles collected were pieces of bark and burnt branches. The data collected on ember's characteristics compared very well to previous experiments. Ember loading ranged from 0.2 to 98 gr/m^2 and most of the particles had a surface area smaller than 100 mm^2. Later, small scale experiments were designed to understand the ignition process of structures. Results from the field experiments were used to determine the range of embers to be used. Four different types of experiments were completed. It was shown that the temperature exposure generated from ember accumulation can be simulated by an electrical heater, but the higher thermal inertia compared to the embers resulted in a lower temperature gradient. It was also shown that in the range of size and mass of the embers collected, it was possible to ignite samples of wood in different geometrical arrangements. Future work will be focused on determining how to incorporate the intensity of the thermal exposure and the time of exposure into a critical factor for ignition.

1. INTRODUCTION

Wildfires are very complex phenomena that can have a significant and disastrous impact on human settlements by endangering lives and affecting public and private properties. It has been calculated that millions of acres and hundreds of structures are destroyed annually by wildfires [1].

The Wildland Urban Interface (WUI) has been defined as "any area where humans and their development meet or intermix with wildland fuel" [2]. This study focuses on a mechanism of wildfire spread at the WUI to wooden structures. The process to be studied is the ignition due to the accumulation of hot embers on specific geometries (angles, wedges or joints of sections). There are many factors involved: from the aspects related to the generation and transport of embers, to landing, accumulation and, subsequently, the parameters that define ignition conditions of the structural elements.

Two different sets of experiments are considered. Large scale experiments allowed obtaining the properties of embers landing on the ground. This information was then used to design small scale experiments that simulated ignition under different conditions.

The topic of wildfires has been studied from many different perspectives. Aspects such as the fatalities associated to rapid changes of wildfire behaviour in several parts of Europe have been previously analysed [3], as well as the impact from an ecological perspective showing the importance of wildfires in the "maintenance of the health of many ecosystems". [2]. This study combines previous understanding on ember generation with research that has been conducted on the parameters driving the ignition of wood under different circumstances.

The trajectory of embers lofted by ground fire plumes (surface fires) has been analysed [1], showing that disks (bark) propagate furthest and have the highest remaining mass fraction upon impact. The ignition of forest litter by firebrands has also been studied [4] using particles of different materials to simulate embers or hot particles to simulate those ejected by power-lines [5]. It was found that ignition has a very high dependence on wind conditions and Fuel Moisture Content (FMC). Home ignitability during wildfires was considered [6], with more focus being made on ignition by radiation from the flame front and the concept of Flux Time Integral being used to account for a defined critical exposure for ignition, which considers the intensity of the heat flux as well as the time of exposure. The importance of ignition by firebrands has been highlighted and it was concluded that the risk of ignition depends on the roof flammability. Similar approaches were used [7] to study ignition by radiation from the flame front in large scale experiments.

Ignition by firebrands has been individually studied as the cause for ignition of structures located in the WUI, [8, [**9**]. A wind tunnel connected to a firebrand generation device was used to create a continuous shower of firebrands. Results were affected by many factors such as the material, angle of impact and burning state of the firebrands. A set of parameters for ignition or no ignition was defined for each case. Finally, the propagation of wildfires due to ember ignition (spotting) was studied [10] and an analysis was completed on the difference between short-range and long-range firebrands. The difference depends on the intensity of the fire plume and the way firebrands are lifted by it. The paper concludes that the current state of knowledge on generation of, and ignition by firebrands is insufficient to develop a predictive model.

The current study aims at using the information gathered from the field to understand the parameters that affect ignition of wooden structures. Only short range embers are considered. For the purpose of this study, short-range embers are defined as those embers lifted by the convective plume with a travel distance in the range of tens of meters. Long range firebrands can travel hundreds of meters and even kilometres.

Ignition of wood has been studied under a radiative heat flux. Some results from past experiments [11[12] are considered, especially with regards to critical parameters that affect ignition and heat transfer trough conduction in the wood.

The influence of temperature, density, porosity and anisotropy on thermal conductivity and diffusivity of wood has been studied [11]. Results showed a dependence on grain direction and temperature of the sample and concluded that heat transfer is not only made of conduction, since the voids in the material are filled with air, which affects the heat transfer and also changes density with temperature. A summary of past experiments was completed with the intention of defining the material properties with the largest effect on the charring rate [12]. This was not achieved since the conditions change for every experiment but five different sections are defined on a wooden sample exposed to a heat flux. These sections are determined by temperature ranges and permit the study of different chemical reactions and physical phenomena in the sample.

Experimental and theoretical studies of the ignition of wood have been completed. A model was designed and it showed good agreement in predicting times to ignition [13]; various air velocities were studied and ignition (smouldering and/or flaming depending on the situation) was observed for incident heat fluxes between 24 and 55 kW/m^2.

Other studies have used the Cone Calorimeter to examine the ignition of wood samples [14]. Comparisons with a theoretical model were made and it was found that the ignition mechanism of wood is different at lower heat fluxes than at higher heat fluxes. The difference is believed to be caused by char oxidation prior to flaming ignition. Good agreement was shown between the model and the experimental results.

Finally, four different species of wood were exposed to different heat fluxes [15]. A one-dimensional integral model, which describes the transient pyrolysis of a semi-infinite charring solid, was designed. Burning depth, thermal penetration and charring depth were predicted by the model and compared to experiments. Incident heat fluxes of 25, 35, 50 and 75 kW/m^2 were used. Ignition was observed. It was not in the scope of this study to use one of the models explained before.

This manuscript is divided into methodology, results and discussion sections. In each section, field and laboratory experiments are separated into subcategories. This work is a continuation of [16], where Houssami et al. collected a first set of properties. Here, the authors intend to use this field data in laboratory experiments in order to eliminate the use of surrogate fuel, such as charcoal. The laboratory work included four series of test: a) inert heating on inert material, b) inert heating on wood, c) active heating on inert material and d) active heating on wood.

2. METHODOLOGY

This section includes the description of the samples used and the measurements conducted. The work is separated into large scale experimentation, which is used for particle characterization, and small scale experimentation, which explores the various facets of firebrand accumulation, such as heat transfer to a solid material and ignition potential of wood.

2.1 FIELD EXPERIMENTS

Large scale experiments were performed in the Pine Barrens in New Jersey, USA, in 2013, 2014 and 2015, with the intention to evaluate the effect of prescribed burning on the intensity of wildfires. Results on the 2013 experiments can be found in [16]. The analysis of this data (wind and intensities) for the 2014 experiment is not yet available. Different variables were measured such as wind velocity, temperature, radiation from the flame front, etc. using measuring towers that were divided into three categories: overstory towers, understory towers and Fire Behaviour Packages. The current study focuses on field data generated in 2014 only. Figure 1 shows a satellite picture of the burning plot with the location of all the measuring towers as well as the ember collection plots (E1, E2 and E3).

For the process of collection of embers, the same procedure used in [16] was employed. Three different ember plots were used to collect falling embers. Every ember plot was constituted of 20 aluminum pans placed over a gypsum board covering an area of 1.4 m^2. The embers collected from the pans were taken back to the field laboratory and measured.

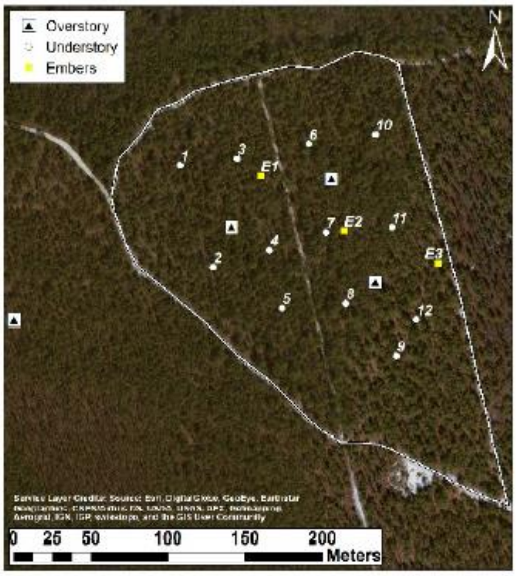


Figure 1. Burning plot and location of measuring towers and ember collection plots.

In 2014, embers were measured using a digital calliper with a precision of ± 0.01 mm. They were divided into two categories: bark or branch. For the bark slices, the width, length and thickness were measured. For the branches, the diameter and the length were measured. All embers were weighted in an electronic scale with a precision of ± 0.01 mg. Embers lighter than 5 mg were not measured individually, but were later collected and their total mass was measured for each plot. Since not all embers for the 2014 experiment could be measured on that year, the remaining particles were measured in 2015 using an imaging algorithm, capable of determining their size from individual photographs taken of each ember. This improved measurement technique is not discussed further as it is not the topic of the paper.

2.2 SMALL SCALE EXPERIMENTS

Laboratory experiments were designed to study the process of wood ignition by ember accumulation. Two main phenomena are studied: the smouldering combustion of the embers, which translates into a heat flux towards the wooden boards, and the decomposition and subsequent ignition of the wood when exposed to a conductive heat flux.

The experimental set up was designed to simulate the accumulation of embers on sample materials, as shown in Figure 2. The table allows for different angles between the boards to be tested, related to different configurations that can be found in wooden constructions.

Redwood and vermiculite samples were used. Vermiculite is a material with many commercial uses, applied mainly for insulation or as a moisture-retentive medium for absorption of liquids. Since vermiculite's thermal properties are similar to those of redwood, samples of this material were used to compare heat flux and temperature profiles generated by embers (vermiculite does not degrade and does not ignite). Each sample had a size of 260x150x20 mm. 12 Thermocouples were used to measure the temperature inside of the wood at different depths.

Figure 2. Table used for small scale experiments on ignition of wood.

Figure 3 shows the distribution of the thermocouples. Heat transfer by conduction was mainly analysed in the top-to-bottom direction (through the wood, x direction in the chosen system of coordinates). Two sets of three thermocouples (FGH and IJK), located at 3, 6 and 9 mm deep served this purpose. The first set (FGH) was located at 5 mm from the edge of the sample and the second one (IJK) at 30 mm.

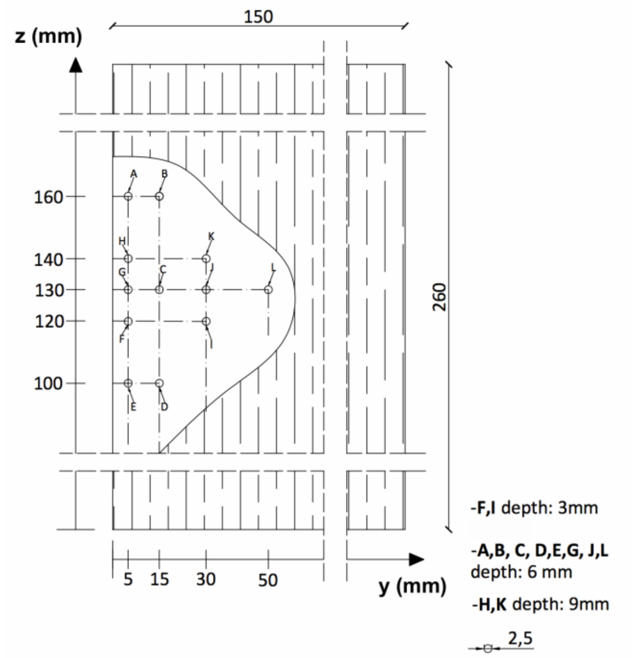


Figure 3. Position and depth of thermocouples in the wood sample.

Table 1 shows a comparison between the thermal properties of redwood (taken from literature) and vermiculite, given by the manufacturer.

Table 1. Properties of wood and vermiculite.

Thermal property	*Redwood[15]*	*Vermiculite*	*Units*
Conductivity	0.19	0.19	W/mK
Density	354	700	kg/m^3
Heat Capacity	3200	995	J/kgK

Four different sets of experiments were designed. Below their characteristics are discussed. The following three definitions are used throughout this work:

- Inert heating: heating by electrical heater
- Active heating: heating by firebrands
- Inert material: vermiculite

2.2 (a) Inert heating on wood.

To analyse the ignition of wood by conduction (convection and radiation are ignored), the first set of experiments used an electrical strip heater to simulate a conductive heat flux into the wood. The heater measured 130x45 mm and had a heating area of 45x45 mm. The heater was clamped to the wood samples using steel C-type clamps.
The electrical heater provided a power of 150 W at a voltage setting of 120 V. A voltage variator was installed, as seen in Figure 4, and the electrical supply was varied between 60V, 90V and 120V. Four different sets of experiments were completed. In these experiments, different designs were tested to measure surface temperature. Only the results of the last one are discussed in this paper, since they were performed with the refined methodology.
Figure 4 shows the experiment set up for experiments type 2.2 (a) and 2.2 (b). Experiments performed with the electrical heater only used half of the experimental table since only one sample is used.

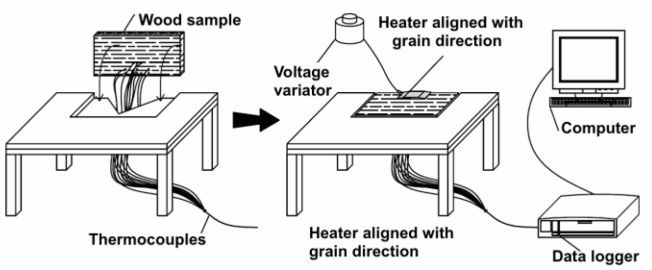


Figure 4. Experimental set-up for experiments 2.2 (a) and 2.2 (b).

2.2 (b) Inert heating on an inert material.

To understand the limitations in the use of the heater and the way the vermiculite would impact the results in the upcoming experiments, the vermiculite was exposed to seven different heat fluxes generated by setting the variator at 60V, 70V, 80V, 90V, 100V, 110V and 120V.

2.2 (c) Active heating on an inert material.

Using the information collected from the field experiments (types of particles, size and mass), it was possible to simulate the impact of burning embers when accumulated. Since the objective was to study and understand the heat flux generated by the embers to the structure, vermiculite boards were used to avoid the process of decomposition of the wood (which in turn affects the overall heat transfer). Several tests were made in an attempt to understand the process and standardize the experimental procedure. Embers were deposited on the boards in a smouldering state. To reach this state, the virgin material was placed in a steel wire basket and then submerged into flames from a small heptane pool fire and for a given time period. The size selection for the virgin material as well as the exposure time to the flames was done by trial and error. The goal was to create firebrands that are comparable in size and mass to the ones found in the field. This same procedure was used for burning embers in experiments 2.2 (d).

2.2 (d) Active heating on wood.

These experiments simulated the ignition of wooden samples by different loads of embers. Although in the beginning charcoal was used to simulate the embers, it was found that this was a poor choice since it simulated poorly the actual firebrands. Particularly, the individual mass of particles was much higher, the shape was inconsistent with what had been found in the field and, perhaps more importantly, charcoal created a layer of ash that acted as an insulator and slowed down the heat transfer to the wood. It is for this reason experiments with charcoal are not discussed.
From the data collected by the large scale experiments, slices of bark were used in different size and mass ranges. Different angles between the wood samples were also studied and the conditions for ignition were determined. Time to ignition was recorded.
The distribution of the thermocouples was constant for all experiments. Experiments that used the electrical heater only used one wood sample (half of the table, as previously mentioned). Experiments that considered burning embers employed two samples of wood or vermiculite but temperature measurements were only made in one of them.
Figure 5 and Figure 6 show photographs taken during initial experiments.

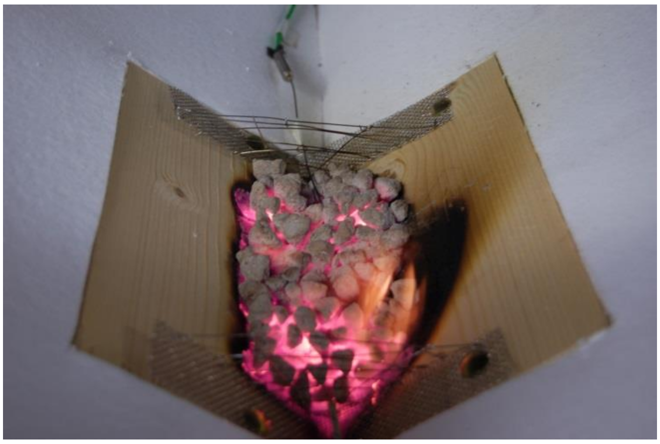


Figure 5. Photograph of initial experiments of active heating on wood. 100 grs of charcoal are used to simulate accumulation of embers.

Figure 6. Photograph taken during experiments with embers and wood. Flaming ignition at the back face.

3. RESULTS

3.1 FIELD EXPERIMENTS (2014)

Table 2 shows a summary of all the particles collected in the three ember plots. The number of particles measured in E2 was much higher (over 1000%) than those collected in E1 and E3. The intensity and wind data has not yet been evaluated. However, video observations at plot E2 indicate that crowing occurred. This can be seen in Figure 7. The ember collection plot 2 is only a few meters outside of the frame of the photograph. The picture is a snap shot of a video on which it can be seen that crowning continued for some time at this location. The crowning behaviour creates much more firebrands because branches, bark and foliage (dead and live) are detached and lofted away. Fire intensity calculations often do not account for the crowning fire behaviour. E1 showed similar fire behaviour than E2 but without crowning. Plot E3 was located at the edge of the burning block and low intensity was observed. This is one explanation for the high number of firebrands in E2. Also seen in Figure 7, is a good example of short range firebrands, which ignite the fuel layer in front of the flame front.

Figure 7. 2014 field experiment; Crowing behaviour just before ember plot 2

Table 2. Number of embers measured per plot.

Particles	*E1*	*E2*	*E3*
Bark	118	1028	14
Branch	15	412	12
Other	8	18	17
Total	141	1458	43

Figure 8 shows the ember distribution by percentage of total number collected. Most of the embers collected are pieces of bark or branch, with some pieces of pine needles and burned pinecones grouped under the category "other". E1 and E2 were located inside of the burning plot and E3 adjacent to the edge

With the exemption of E3, in E1 and E2 bark constitutes the majority of particles collected (total embers). Figure 8 shows that bark represents more than 80% of the total number of particles measured in E1, 70% of the total measured in E2 and more than 30% in E3.

When divided by mass, bark represents 79% of the mass in E1, 45% in E2 and 34% in E3. By contrast, "other" particles represent less than 5% of the mass in plots 1 and 2 and less than 15% in plot 3. For this reason, only data associated to bark and branches is analysed. Furthermore, only bark is used to simulate embers in the small scale experiments.

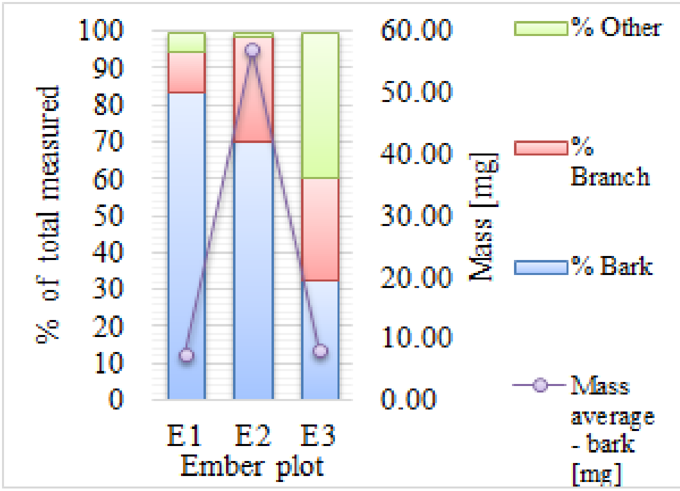


Figure 8. Distribution of embers by collection plot. Percentages show distribution with respect to total number of particles collected.

The total load collected by plot was 0.8 gr/m^2, 98 gr/m^2 and 0.2 gr/m^2, for E1, E2 and E3, respectively. Figure 8 also shows the average mass by plot. The average mass for E2 is much higher than that calculated for the other plots. This is due to the fact that heavier individual particles were collected in that plot.

Figure 9 shows thickness values for bark slices collected in plots E1&E3 and in E2. The average value is represented by a triangular marker and the bars show the range defined by the minimum and maximum values. For embers collected in plots 1 and 3, the individual thickness of every particle was measured. However, for slices collected in plot 2, the thickness was measured for only a sample of then (116 bark slices representing 8% of the total). For particles collected in E1 and E3, length and width was measured individually by particle. It is then assumed that all particles have a rectangular shape and the area is calculated as width × length. For particles collected in E2, the area was determined using software that calculated the total area of the particle from individual photographs. A reference length was defined in every photograph by drawing a 1 cm line in the paper were the embers were photographed, and the total area is calculated by the number of pixels that the ember occupies in the picture. The software has a precision of 4.84 x 10^{-5} m^2.

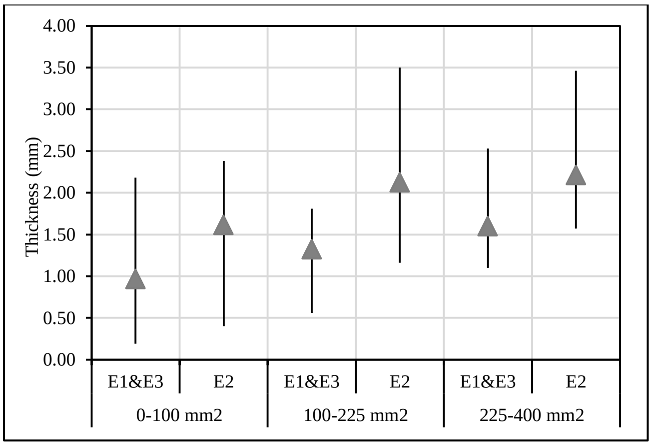
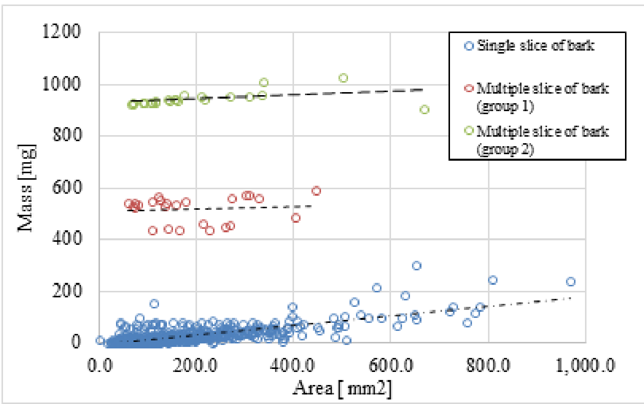


Figure 9. Thickness of bark slices for different surface areas. Two sets of data are considered: embers collected in E1&E3 and embers collected in E2. Average value is shown by the marker and range is defined by minimum and maximum values.

Figure 10 shows the photograph of a single bark slice collected in E2. Figure 11



shows mass vs area for all bark slices collected. The three colours show very different mass ranges, which is attributed to multiple slices of bark. Only particles from ember plot 2 are shown since the area measured is much more reliable.

Figure 10. Photograph of bark slice.

Bark is constituted by several slices of wood that grow on top of each other during the development of the tree. Depending on the intensity of the fire, the type of three and the wind conditions (both environmental and fire induced), bark slices that are detached from the three trunk to become embers may still be grouped. From this analysis it is clear that the three mass categories (highlighted by colours in the figure) are not random but correspond to different numbers of slices of bark grouped together. This will impact the way the embers burn and their overall travel distance and remaining energy at landing.

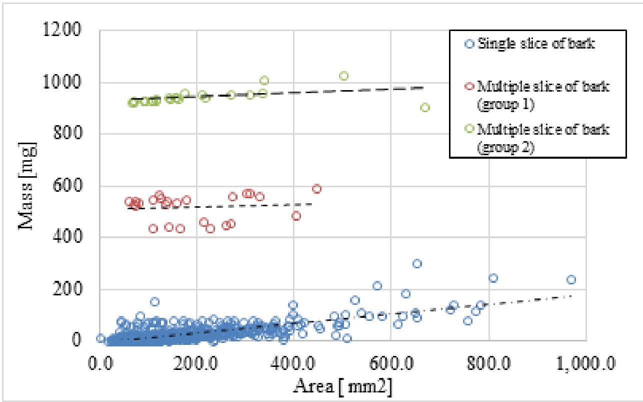


Figure 11. Mass vs area for bark slices. Colours are shown to accentuate the three different mass groups. The lines are linear trend line for each group.

3.2 SMALL SCALE EXPERIMENTS

Results are be shown for every set of experiments and independently analysed. In the discussion section a connection is made between them.

3.2 (a) Inert heating on wood.

Four sets of experiments were completed. As explained before, only the results from the final set are shown. The objective was to study the ignition of wood by conduction and to understand the limitations associated to the experimental set up

with the idea of possibly establishing an ignition criterion that would not depend on the characteristics of the embers, such as mass, size and type (bark, branch, etc.).
Figure 12 shows a schematic of the heat transfer scenario with the position of the thermocouples.

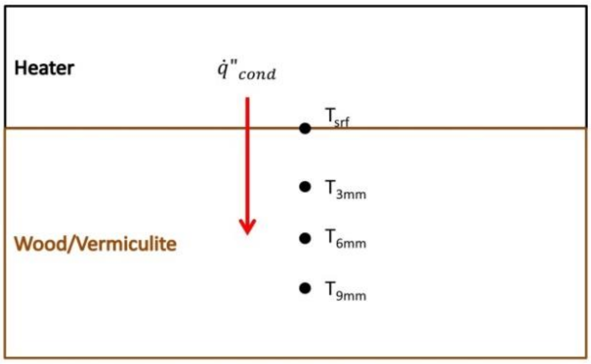


Figure 12. Schematic of heat transfer scenario; heater and wood/vermiculite sample are insulated on exterior sides.

Figure 13 and Figure 14 shows temperature profiles (top to bottom) at 5 mm (left) and 30 mm (right) from the edge. The heater was set to 90V. Figure 13 shows results for experiments where surface temperature was measured (showed by the dashed lines). Surface temperature refers to the temperature at the surface of contact between the heater and the wood.

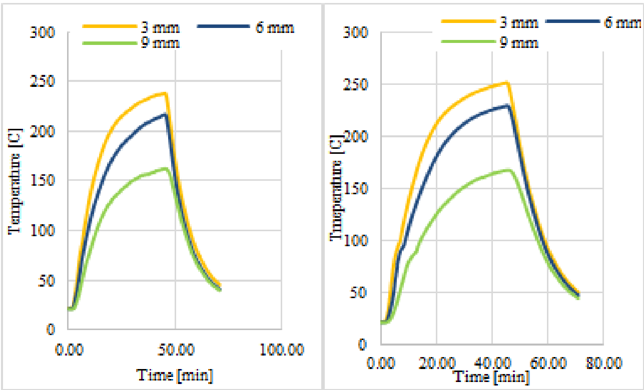


Figure 14 shows experiments were the surface temperature was not measured. Results showed that at 60V, the heat flux provided by the heater was not sufficient to initiate charring in the wood. At 90V, charring was observed but the process was not self-sustained. The heater was turned off after 30 min. The dashed lines in the graphs below show the surface temperature measured with two 0.25 mm, sheathed thermocouples placed between the heater and the wood sample.
This comparison served to analyse the impact of the surface temperature measurements on the heat transfer process. Wood samples were insulated on the sides and back face. It was proven that insulation permitted a better approximation to a one dimensional problem when analysing heat transfer from top to bottom at both locations. Maximum temperatures reached inside of the wood are higher for experiments with no surface temperature measurements (see Figure 14). This is because a small gap is created when the thermocouple is placed between the heater and wood. This flue space created a means for convection losses to occur. In the calculation for the heat flux to the sample, only conduction is considered. For this reason, internal temperature measurements from tests with no surface temperature measurements are used. The idea of these experiments was to understand the degradation process of the wood so that a criterion of ignition can be defined based on thermal exposure and temperature gradient in the wood.

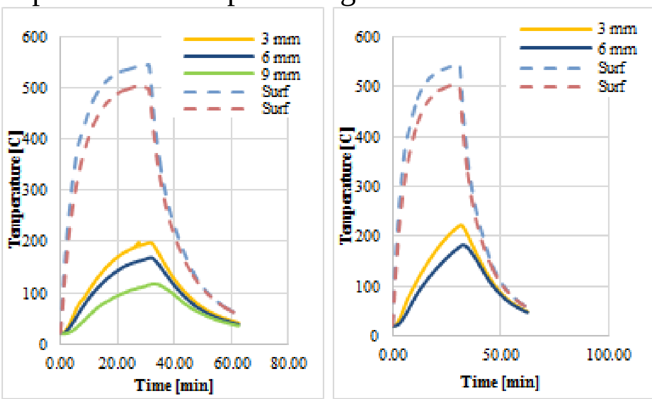


Figure 13. Temperature profiles. 90 V. Left: 5 mm from the edge. Right: 30 mm from the edge. Dashed lines show surface temperature. Experiments with surface temperature measurements.

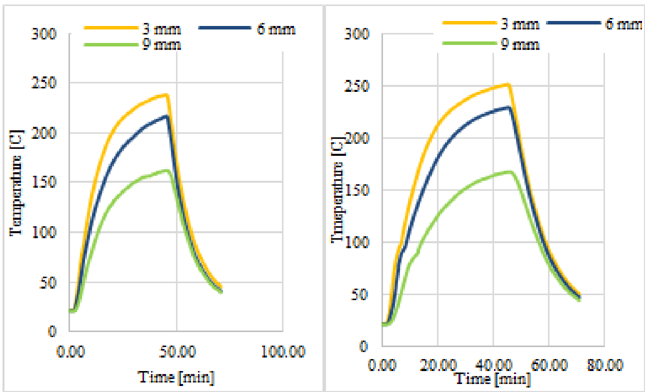


Figure 14. Temperature profiles. 90 V. Left: 5mm from the edge. Right: 30 mm from the edge. Experiments without surface temperature measurements.

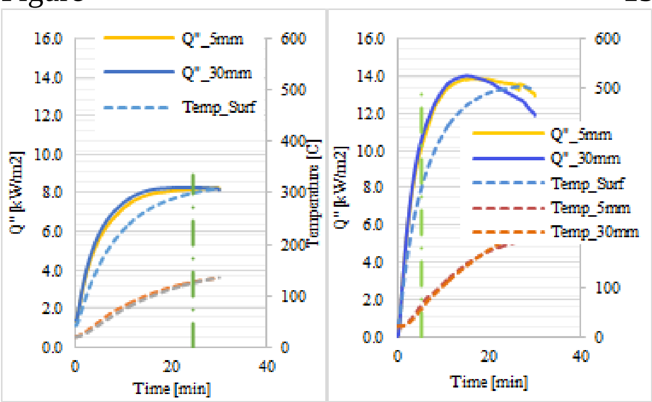
In order to compare this experiment with the following sets (inert heating on inert material and active heating on inert material), a value of conductive heat flux trough the wood was calculated. Since the idea is to define an ignition criterion, charring is not analysed. It is assumed that charring occurs at 300 °C, at which point the chemical and physical changes in the wood have an important influence on the thermal behaviour of the sample. It is for these reasons that the analysis extends solely to pre-charring behaviour. For a first approximation, the conductivity is assumed to be independent of the temperature of the sample. The conductive heat flux is estimated as follows:

$$Q" = \frac{k * (T_{surface} - T_{6\,mm})}{0.006\,meters}$$

Assumptions considered

1. Constant conductivity (not dependant on temperature).
2. Heat flux calculated between surface and 3 mm.
3. One dimensional situation.
4. Conduction is the only mode of heat transfer.
5. Heat losses are negligible due to insulation of the material.

Figure 15



shows the heat flux calculated by the previous equation. The green line in the graph shows the point at which a temperature of 300 °C is reached at the surface of the sample (charring starts to occur). Only the process to the left of this line is considered. The graph on the left shows results for a heater supply of 60 V and the one on the right for a supply of 90V. The upper (blue) dashed line shows the evolution of the surface temperature, the lower dashed lines show temperature in the sample at a depth of 3 mm (both 5 mm and 30 mm from the edge). Maximum heat flux value in the considered range is 10 kW/m^2. Even considering the error associated to this calculatioin, mainly due to a constant conductivity assumption, this value is comparble but lower to common incident heat fluxes (radiation) for ignition found in the literature (see [13] and [15]) . During the test (90 V), charring was observed and localized smouldering but a self-sustained oxidyzing reaction was not attained.

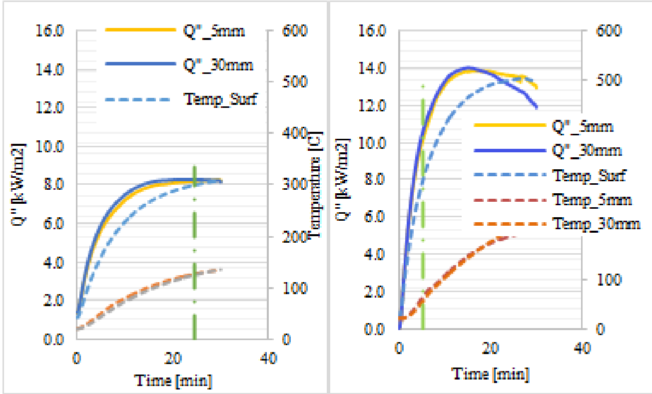


Figure 15. Heat flux calculated between the surface and the 3 mm deep thermocouple. Left: 60V. Right: 90 V. Green line shows time at which surface temperature reached 300° C.

3.2 (b) Inert heating on an inert material.

Figure 16 shows the heat flux values from the surface to a 6 mm depth from the edge. Solid line show heat flux at 5 mm (subscript 1) from the edge and dashed at 30 mm (subscript 2). Seven different voltage settings were used. The heat transfer calculations follow the same model than what was described in the previous section. The difference between the heat fluxes at the two locations increases as the supply voltage is increased and this is due to the fact that losses at the edge increase as the temperature in the sample increases. The edge of the sample that is being di

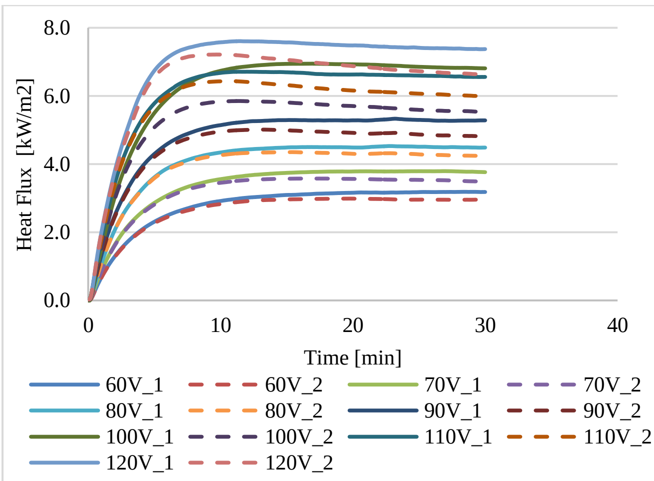


Figure 16. Heat flux from top to bottom. Electrical heater on vermiculite. Solid lines show heat flux at 5 mm from the edge (subscript 1) and dashed lines show heat flux at 30 mm from the edge (subscript 2).

Bigger losses mean lower temperatures at the edge and the heat flux increases as the difference with the surface temperature is larger. Maximum heat flux at 90 V is around 5 kW/m^2, which is lower than what was calculated for inert heating on the wood. However, ρkc (thermal inertia) of wood is larger than that of vermiculite. This means that vermiculite stores less energy than wood and the temperature change (and heat flux trough the material) differs.

3.2 (c) Active heating on an inert material.

Three main parameters were varied in these experiments: the size of the embers, the total mass and the angle between the samples (180° -flat- and 120°). Between 50-80 % of the bark collected in the field in all plots had a size of approximate 100 mm^2. So, after several tests it was decided to maintain the size of the embers constant and vary the total mass of embers used for each experiment. This reasoning was also applied to experiments in 3.2 (d). The slices of bark were deposited on top of the samples in a circular area of 78.53 cm^2 (diameter of 10 cm). Flat (180°) and angled (120°) configurations were tested with different masses of embers and then compared with the values obtained for the experiments performed on wood were ignition was observed. Figure 17 shows the heat flux calculated for 40 g. of embers at 180°, which is the maximum mass at which flaming ignition was not observed (intervals of 20 g. were used and flaming ignition was observed on the back side of the sample at all tests performed with 60 g. of embers).

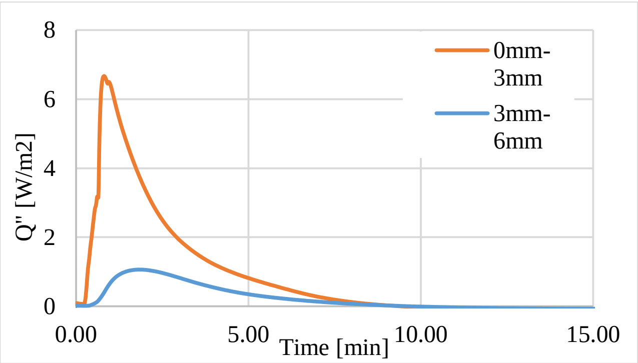


Figure 17. Heat flux values determined at different depths inside of the wood sample. 40 grs of bark (weighted previous to burning) placed on vermiculite boards.

3.2 (d) Active heating on wood.

Final experiments attempted to replicate the ignition of wood under an accumulation of embers. As mentioned before, ignition was observed in a flat configuration for 60 g. of embers (pre-burning). Flaming ignition came as a result of a continuous smouldering process that led to a degradation of the wood, and after there was a complete penetration of the sample, the additional intake of air as well as convection on the back face of the sample resulted in the appearance of flames In cases where an angle between the samples was studied, flaming was observed in the back face of the samples (See Figure 6). This has very important implications since in real constructions; there are layers of insulation that can ignite easily if the outer shell is penetrated, facilitating the fire spread in the structure.

4. DISCUSSION

The field experiments allowed for a characterization of the embers in the field. Data shows that most of the embers were slices of bark or branch, and that a big percentage of them fall within a given range of mass and size. The highest loading by area of 98 gr/m^2 (collection on the ground) corresponds very well with critical values found for ignition in the small scale experiments. This loading was found in E2 where visual observations from video footage indicated crowning fire behaviour. Collection plots E1 and E3 did not experience crowing fire behaviour, which resulted in a lower firebrand generation.
Since the ignition process depends on accumulation of embers in a critical location, it is assumed that the total possible mass to be collected in a wedge does not need to be scaled for the experiments performed. This means that it is expected that all the embers falling in a relatively large surface (1, 2 or 3 m^2) would accumulate in a small area, similar to the area considered in the small scale experiments. For this reason, it is possible to directly compare the total mass collected at the field experiments with the mass used in the small scale experiments.
Ignition was observed when 60 g. of embers were used. This mass is weighted before burning so the actual mass deposited is much lower, with some initial experiments showing a mass reduction of approximately 60%.
The collection of embers was done for a prescribed fire situation. Prescribed burning is used as a way to reduce fuel loading in a controlled fashion, so prescribed fires usually present lower intensities than wildfires. However,

the intensities were allowed to be higher than usual (including crown fire) to accommodate the needs of this study. Considering that larger fires are more likely to create a larger quantity of embers, the mass used for the small scale experiments correspond very well with what could be expected in a real situation.
It is assumed that charring occurs at 300 °C, at which point the analysis stops since it falls out of the scope of this work (where the goal is to define a criteria for smoldering or flaming ignition under ember accumulation). The problem was assumed to be one dimensional, in which case isothermal lines progress perpendicular to the surface of the samples. This assumption is necessary since it permits the comparison between 5 mm and 30 from the edge, but also because the thermocouples (3, 6 and 9 mm in depth) are located at a horizontal distance of 10 mm from each other, to avoid crossed influence. It was proven that by insulating the samples the assumption was relatively accurate. This was done by analysing the difference in time it took the thermocouples at both locations to reach 100° C. At 60V, 90V and 120V the time difference was 20, 5 and 4 minutes, respectively, when the samples were not insulated. However, insulation of the samples led to differences at all voltage settings of 2 minutes or less.
The heat transfer model does not include losses due to convection or radiation, which still exist to an unknown magnitude. It is assumed that there is a perfect contact between the heater and the wood at all moments during the experiment until charring occurs. Observations showed that this is not the case and there can be separation between the heater and the wood due to shrinkage, i.e. decomposition, of the sample that decreases the efficiency of the conductive heat transfer. It also impacts the development of smouldering combustion at the surface of the sample, since an air current increases convective losses but also increases oxygen supply which speeds up the oxidative reaction.
The heat flux generated by the heater, approximately 7 kW/m^2 on vermiculite, compares very well to the value obtained from 40 g. of embers (with an area of 100 mm^2 in a flat disposition) on vermiculite, approximately, 9 kW/m^2. At 40 g. of embers, in a flat configuration, there was no flaming ignition of the samples.
The experiments performed do not account for the influence of wind. The heater allows for a closer study of ignition by conduction of wood, but it constrains the oxygen supply at the surface (since it occupies the total surface of contact) and this may prevent smouldering ignition at lower heat fluxes.

5. CONCLUSIONS

Studies have shown that ignition of wooden structures by falling embers constitutes a significant problem in the Wildland Urban Interface during wildfires. This study analysed the data collected from field tests regarding the collection of falling embers and incorporated small scale experiments to understand the process of heat transfer and ignition by conduction of wood. Four different sets of experiments were designed to evaluate, both separately and in conjunction, the influence of the smouldering of the embers and the degradation of the wood due to thermal exposure.
From the information in gathered at the field, it was possible to classify the embers by categories such as type, size and mass. Most of the embers collected came from bark slices that detached from the trees as the fire front passed and during post smouldering of the vegetation. It was found that depending on the location, up to 98 gr/m^2 of firebrands can be collected. Most of the slices had a cross sectional area of approximately 100 mm^2. The information gathered in the field was then used to design small scale experiments to model the ignition of wood structures by accumulation of embers. An electrical heater was used in two sets of experiments to model the heat flux generated by the embers. It was found that similar values are reached and no self-sustained ignition could be attained. Flaming was not observed. In the remaining experiments, bark slices were burned and then deposited on top of vermiculite and wood samples. Experiments with vermiculite facilitated the calculation of a heat flux since vermiculite does not degrade or ignite like wood. Experiments on wood showed that at a flat configuration, flaming ignition can be observed when 60 grs. of embers (measured previous to burning) are used.
A more comprehensive model still needs to be designed that accounts for the influence of smouldering embers on wood ignition by

conduction, considering changes in conductivity and looking to understand the impact of the advancement of the charring front on self-sustained burning. Future work should be directed at understanding how to replicate the thermal exposure of the embers with the electrical heater and then using the experimental set up to define ignition criterion for different types of wood. By relating the heat flux generated by falling embers to a given electrical supply of the heater, it could be possible to model the embers as a boundary condition for the wood elements.

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